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“Power Factor Improvement”

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Abstract

In this experiment, the operation and the behavior of a single and three- phase induction motors were studied as well as doing a power factor improvement by adding capacitor bank in order to supply the reactive power to the motor and reduce current drawn by it.

In single phase induction motor, it was observed that as the value of capacitance added to the motor increases, the motor current decreases while using the same torque values and so power factor is improved. However, in three-phase motor operation, the two-wattmeter method gave no accurate results of the measured power quantities so the experimental judgment on the behavior could not be drawn. The calculated value of reactive power for each value of capacitance added to the motor was fairly close to the difference between the initial and final reactive power supplied to the motor.

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Chapter 1

Introduction

The power factor of an AC electrical power system is defined as the ratio of the real power flowing to the load to the apparent power in the circuit. More the inductive the circuit nature is, more energy losses and less power factor. Less the inductive the circuit nature is, less energy losses and less power factor. Less the Capacitive the circuit nature is, more energy losses and less power factor. More the Capacitive the circuit nature is, less energy losses and less power factor. Improving the power factor is done for economic reasons by factories and industrial loads. The idea behind this lies in reducing the total current consumed by the load while maintaining the same average power consumption .

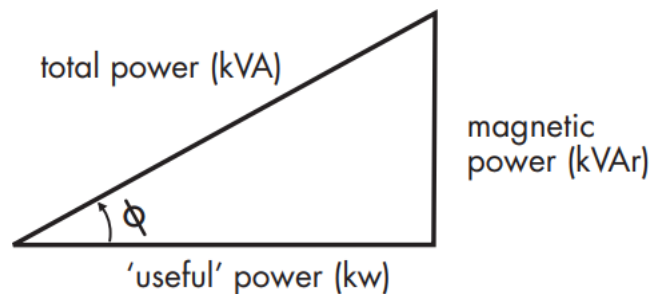


Fig. 1.1: Power Phasor Diagram

This is normally achieved by the addition of capacitors to the electrical network which compensate for the reactive power demand of the inductive load and thus reduce the burden on the supply. There should be no effect on the operation of the equipment. To reduce losses in the distribution system, and to reduce the electricity bill, power factor correction, usually in the form of capacitors, is added to neutralize as much of the magnetizing current as possible. Capacitors contained in most power factor correction equipment draw current that

leads the voltage, thus producing a leading power factor. If capacitors are connected to a circuit that operates at a nominally lagging power factor, the extent that the circuit lags is reduced proportionately.

The benefits that can be achieved by applying the correct power factor correction are:

- Environmental benefit. Reduction of power consumption due to improved energy efficiency. Reduced power consumption means less greenhouse gas emissions and fossil fuel depletion by power stations.
- Reduction of electricity bills .
- Extra kVA available from the existing supply .
- Reduction of $I^2 R$ losses in transformers and distribution equipment .
- Reduction of voltage drop in long cables.
- Extended equipment life – Reduced electrical burden on cables and electrical components.

Power factor correction is achieved by the addition of capacitors in parallel with the connected motor or lighting circuits and can be applied at the equipment, distribution board or at the origin of the installation. Static power factor correction can be applied at each individual motor by connecting the correction capacitors to the motor starter. A disadvantage can occur when the load on the motor changes and can result in under or over correction. Static power factor correction must not be applied at the output of a variable speed drive, solid state soft starter or inverter as the capacitors can cause serious damage to the electronic components. Over-correction should not occur if the power factor correction is correctly sized. Typically the power factor correction for an individual motor is based on the non load (magnetizing) power since the reactive load of a motor is comparatively constant compared to actual kW load over compensation should be avoided. Care should be taken when applying power factor correction star/delta type control so that the capacitors are not subjected to rapid on-off-on conditions. Typically the correction would be placed on either the Main or Delta contactor circuits.

the following set of equations can show how the power factor can be improved ,: Assuming the motor is supplied by a voltage source of V_{rms} , and the real power consumption is P_{avg} , initial reactive power of Q_{in} , final reactive power of Q_f , initial power factor PF_1 , corrected power factor PF_2 . The goal here is to find the formula of correction capacitor C to be installed with the motor in order to make it operate at PF_2 [1].

$$\begin{aligned}
 Q_{in} &= P_{avg} \tan(\cos^{-1}(PF_1)) \\
 Q_f &= P_{avg} \tan(\cos^{-1}(PF_2)) \\
 \Delta Q &= Q_f - Q_{in} \\
 Q_C &= -V_{rms}^2 * \omega * C \\
 C &= \frac{\Delta Q}{-V_{rms}^2 * \omega}, \tag{1}
 \end{aligned}$$

Another set of formulas are needed to do calculations in section 2 is provided in (2) :

$$\begin{aligned}
 S &= VI \\
 Q_{in} &= S^2 - P_{avg}^2 \\
 PF &= \frac{P_{avg}}{S}, \tag{2}
 \end{aligned}$$

where S apparent power in [VA] , Q_{in} Reactive Power in [VAR] ,and PF power factor

The two-watt metric method was used in three-phase motors to measure the amount of three-phase power. This method is explained here to be familiar with way the three-phase power is measured[1]. Assume there are two wattmeters , first one between phase A and B , and the second one between phase C and B . The goal here is to prove that the sum of the two wattmeters' readings will result in total three phase power measurement:

Wattmeter 1 reading :

$$\begin{aligned}
 W_1 &= V_{AB} I_{aA} \cos \vartheta_1 \\
 &= V_L I_L \cos \vartheta_1 \tag{3}
 \end{aligned}$$

Wattmeter 2 reading:

$$\begin{aligned} W_2 &= V_{CB} I_{cC} \cos \vartheta_2 \\ &= V_L I_L \cos \vartheta_2 \end{aligned} \quad (4)$$

where V_{AB} , V_{CB} , I_{aA} , I_{cC} , are respectively line voltage between A and B [V], line voltage between C and B [V], line current through line a-A [A], and line current through c-C [A]

Writing (3) and (4) in terms of the impedance angle ϕ , which is the phase angle between phase voltage and current, (3) & (4) will become:

$$\begin{aligned} W_1 &= V_L I_L \cos(\phi + 30^\circ), \\ W_2 &= V_L I_L \cos(\phi - 30^\circ). \end{aligned} \quad (5)$$

To find the total power, the sum of W_1 and W_2 is taken:

$$\begin{aligned} P_T &= W_1 + W_2 = 2V_L I_L \cos(\phi) \cos(30^\circ) \\ &= \sqrt{3} V_L I_L \cos(\phi) \end{aligned} \quad (6)$$

Chapter 2

Procedure and Discussion

In this Chapter, a qualitative approach is followed and discussed to study the effect of adding capacitor bank with different values on the power factor.

2.1 Single Phase Induction Motor

This section aims to study the behaviour of a single-phase induction motor supplied by a 220V single-phase source and examine the effect of adding a correction capacitor bank on the power, input current, and power factor.

2.1.1 Single Phase Induction Motor Behaviour

AC induction motors, also known as asynchronous motors, use a rotating magnetic field to produce torque. The rotating magnetic field is easily achieved in three-phase asynchronous motors because the phase angle offset between the individual phases is 120 degrees. However, single-phase AC motors require external circuitry, which creates the phase angle offset in order to produce a rotating magnetic field. This circuitry can be realized using advanced power electronics, or more simply using a motor capacitor.

Figure 2.1 represents a capacitor start single phase induction motor. The torque applied to this motor was increased in steps of 0.2N.m up to 0.4N.m. Motor start capacitors are used during the motor start-up phase and are disconnected from the circuit once the rotor reaches a predetermined speed, which is usually about 75% of the maximum speed for that motor type [2].

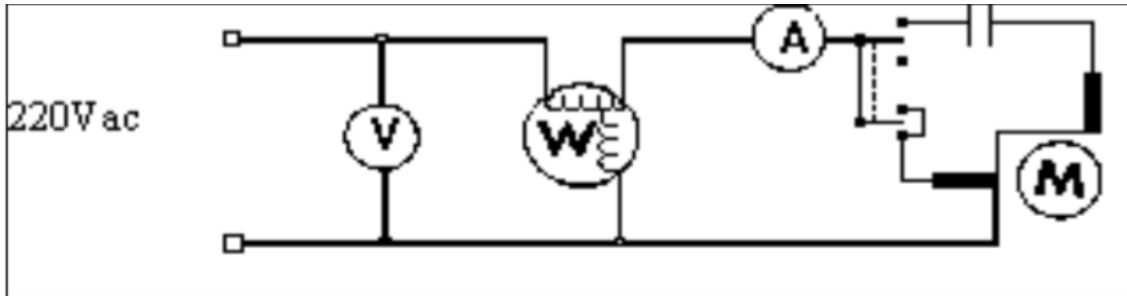


Fig. 2.1: Capacitor Start Motor

The following table presents the measurements of speed, input current, voltage, and input power, the apparent and reactive power, and power factor.

| Torque [N.m] | Speed [rpm] | I_{in} [A] | V [V] | Pin [W] | S [VA] | PF | Q [VAR] |
|-----------------|----------------|-----------------|----------|------------|-----------|-------|------------|
| 0.0 | 1400 | 1.36 | 214 | 92 | 291 | 0.314 | 276 |
| 0.2 | 1450 | 1.37 | 2212.5 | 116 | 292 | 0.417 | 267.97 |
| 0.4 | 1380 | 1.39 | 210.7 | 143 | 293 | 0.484 | 255.7 |

Table 1: Measured and calculated quantities of the single-phase induction motor with zero shunt capacitance.

2.1.2 Single Phase Induction Motor With Shunt Capacitance

This time a shunt capacitor was connected across the motor as shown in Figure 2.2. The same measurements and calculations were done with capacitor values of 3 μ F, 5 μ F.

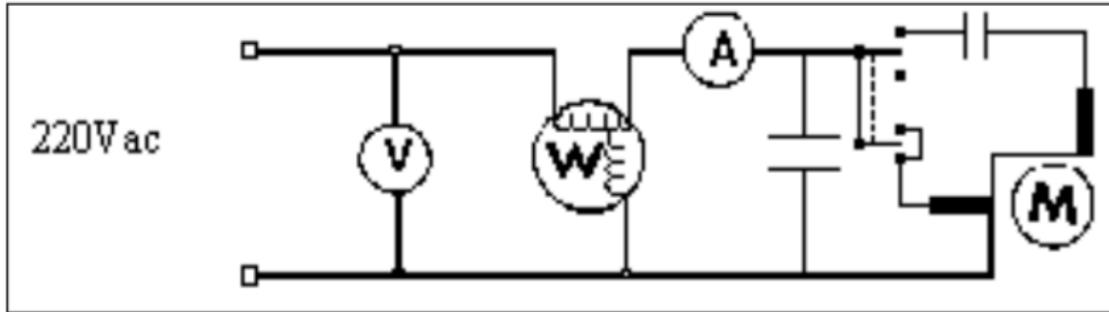


Fig. 2.2: Capacitor Start Motor with Shunt Capacitor

- For $C_{shunt} = 3\mu F$

| Torque [N.m] | Speed [rpm] | I_{in} [A] | V [V] | Pin [W] | S [VA] | PF | Q [VAR] |
|-----------------|----------------|-----------------|----------|------------|-----------|-------|------------|
| 0.0 | 1400 | 1.119 | 216 | 92.2 | 241.7 | 0.385 | 223.4 |
| 0.2 | 1450 | 1.14 | 213 | 122 | 242.82 | 0.502 | 209.9 |
| 0.4 | 1380 | 1.2 | 210.6 | 153.7 | 184.44 | 0.608 | 101.8 |

Table 2: Measured and calculated quantities of the single phase induction motor with 3 μ F shunt capacitance

- For $C_{shunt} = 5\mu F$

| Torque [N.m] | Speed [rpm] | I_{in} [A] | V [V] | Pin [W] | S [VA] | PF | Q [VAR] |
|-----------------|----------------|-----------------|----------|------------|-----------|-------|------------|
| 0.0 | 1400 | 1 | 217 | 93.1 | 217 | 0.428 | 196 |
| 0.2 | 1450 | 1.034 | 214.7 | 121.6 | 221.9 | 0.547 | 185.6 |
| 0.4 | 1380 | 1.105 | 211 | 154 | 233.115 | 0.66 | 174.8 |

Table 3: Measured and calculated quantities of the single-phase induction motor with 5 μ F shunt capacitance

The following plot was obtained using Matlab for power factor versus motor torque for different capacitor values from the measured data in previous tables.

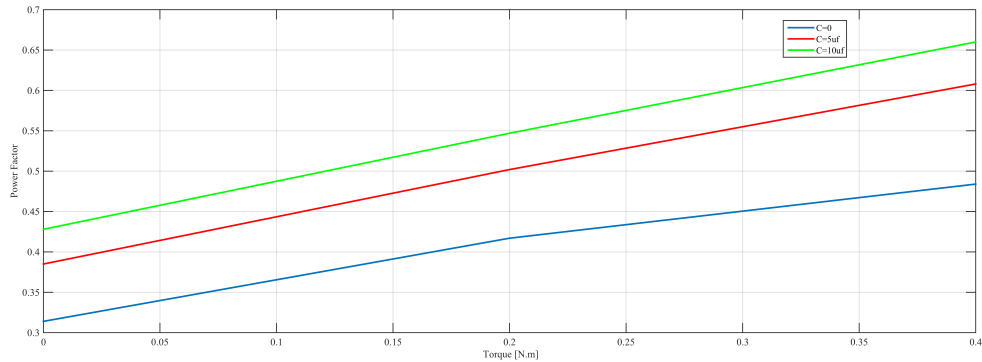


Fig. 2.3: The Effect of adding Capacitor shunt Bank to the Induction Motor.

➤ Then the following calculations were done :

$$Q_c = -V_{rms}^2 (2 * \pi * f) * C$$

- **For C= 3uF**

$$f=50Hz, V_{rms}=218V$$

$$Q_c = -44.7Var$$

$$Q_i = 221.02Var$$

$$Q_f = 200.7Var$$

$$\Delta Q = Q_f - Q_i = -20.3 Var$$

- **For C= 5uF**

$$f=50Hz, V_{rms}=218.7V$$

$$Q_c = -75Var$$

$$Q_i = 196.5Var$$

$$Q_f = 175.2Var$$

$$\Delta Q = Q_f - Q_i = -21.2 Var$$

2.2 Three Phase Induction Motor

This section aims to study the behaviour of a three-phase induction motor supplied by a 220V single-phase source and to see the effect of adding a correction capacitor on the power factor which will be connected in both Δ and wye.

2.2.1 Three Phase Induction Motor Δ Connected With Zero Shunt Capacitance.

Figure 2.4 represents the connection diagram of a Δ - connected three-phase induction motor. The torque applied to this motor was increased in steps of 0.2 N.m up to 0.4N.m .The two-wattmeter method was used to measure the total input power .

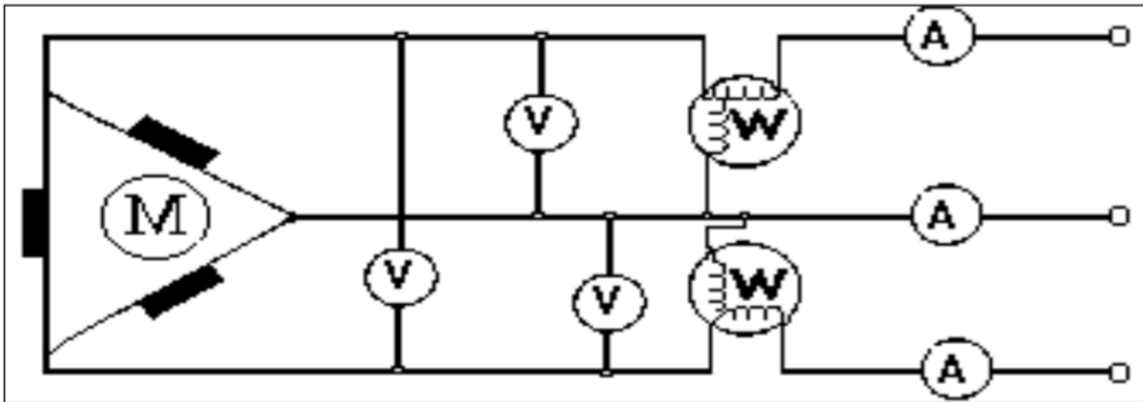


Fig. 2.4: Δ Connected Three Phase Induction Motor

The following table presents the measurements of speed , input current , voltage ,and input power , , and power factor .

| Torque [N.m] | Speed [rpm] | I_1 [A] | I_2 [A] | V_1 [V] | V_2 [V] | P_{in1} [W] | P_{in2} [W] | P_{total} [W] | PF |
|-----------------|----------------|--------------|--------------|--------------|--------------|------------------|------------------|--------------------|------|
| 0.0 | 1400 | 0.5 | 0.5 | 500 | 500 | 75 | 2.5 | 77.5 | 0.64 |
| 0.2 | 1350 | 0.2 | 0.2 | 500 | 200 | 78 | 4.8 | 82.8 | 0.42 |
| 0.4 | 1300 | 0.5 | 0.5 | 500 | 200 | 60.5 | 30 | 90.5 | 0.17 |

Table 4: Measured and calculated quantities of the three-phase induction motor with zero correction capacitance

2.2.2 Three Phase Induction Motor Δ Connected With Δ Shunt Capacitance.

Figure 2.4 represents the connection diagram of a Δ - connected three-phase induction motor with Δ - connected capacitors each of $2\mu\text{F}$. The torque applied to this motor was increased in steps of 0.2 N.m up to 0.4N.m .The two-wattmeter method was used to measure the total input power .

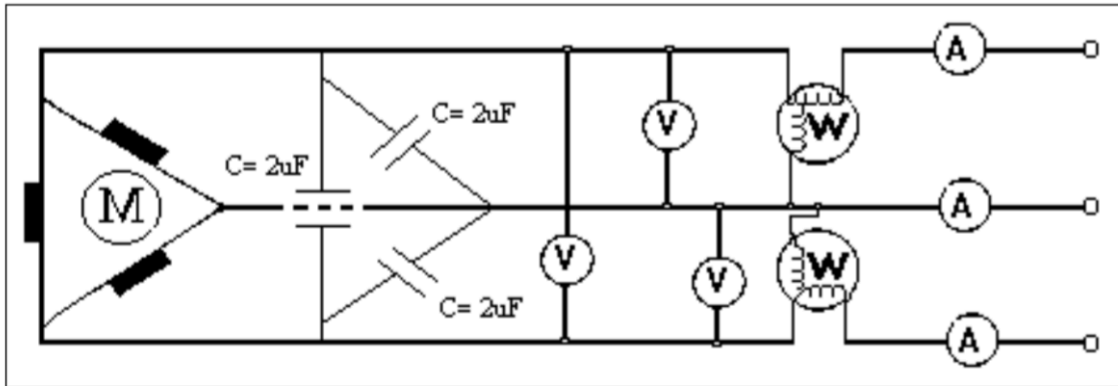


Fig. 2.5: 3-phase induction motor Δ -connected with capacitors Δ -connected

The following table presents the measurements of speed , input current , voltage ,and input power , , and power factor .

| Torque [N.m] | Speed [rpm] | I_1 [A] | I_2 [A] | V_1 [V] | V_2 [V] | P_{in1} [W] | P_{in2} [W] | P_{total} [W] | PF |
|-----------------|----------------|--------------|--------------|--------------|--------------|------------------|------------------|--------------------|------|
| 0.0 | 1400 | 0.5 | 0.1 | 500 | 500 | 25 | 25 | 50 | 0.65 |
| 0.2 | 1350 | 0.5 | 0.5 | 500 | 500 | 37.5 | 50 | 87.5 | 0.9 |
| 0.4 | 1300 | 0.5 | 0.5 | 500 | 500 | 50 | 62.5 | 112.5 | 0.75 |

Table 5: Measured and calculated quantities of the three-phase induction motor with Δ -connected $2\mu\text{F}$ capacitance

2.2.3 Three Phase Induction Motor Δ Connected With Wye Shunt Capacitance.

Figure 2.5 represents the connection diagram of a Δ - connected three-phase induction motor with wye- connected capacitors each of $2\mu\text{F}$. The torque applied to this motor was increased in steps of 0.2 N.m up to 0.4N.m .The two-wattmeter method was used to measure the total input power .

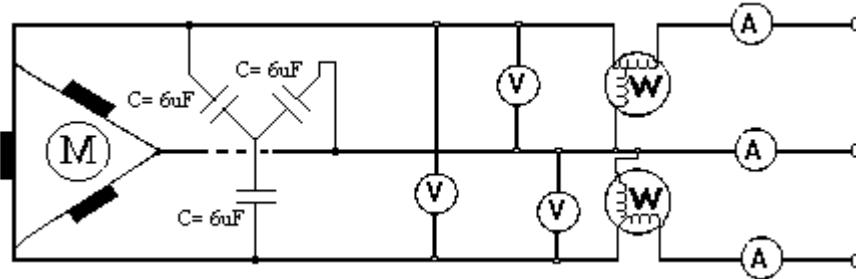


Fig. 2.6: 3-phase induction motor Δ -connected with capacitors wye-connected

The following table presents the measurements of speed , input current , voltage , and input power , , and power factor .

| Torque [N.m] | Speed [rpm] | I_1 [A] | I_2 [A] | V_1 [V] | V_2 [V] | P_{in1} [W] | P_{in2} [W] | P_{total} [W] | PF |
|-----------------|----------------|--------------|--------------|--------------|--------------|------------------|------------------|--------------------|------|
| 0.0 | 1400 | 0.2 | 0.2 | 500 | 500 | 29 | 20 | 49 | 0.64 |
| 0.2 | 1350 | 0.5 | 0.5 | 500 | 500 | 50 | 50 | 100 | 100 |
| 0.4 | 1300 | 0.5 | 0.5 | 500 | 500 | 50 | 55 | 105 | 0.17 |

Table 6: Measured and calculated quantities of the three-phase induction motor with Y- connected $6\mu\text{F}$ capacitance.

The two-wattmeter method used to measure the total power in three phase motor circuits has produced non-accurate measurements of power which led to some errors while doing related calculations .

Conclusion

This experiment focused on studying the behaviour of single and three- phase induction motors. The capacitor reactive power compensation method was presented and used to improve the power factor of induction motors. It was shown that as the capacitance added to the motor is increases, the more the power factor improves for same power conditions and the more the motor current is reduced. Capacitors are reactive power supplying components, when capacitors are added in parallel to the inductive load, the inductive effect will be cancelled out. However, beyond a certain value of capacitance, the reactive power becomes in the negative region and the apparent power does not decrease any more but starts increasing again which causes the power factor to decrease to lower values than one. In addition to that , the theoretical calculated value of reactive power to be supplied by the capacitor was found to be fairly close to the difference between final and initial values of reactive power consumed by the single phase induction motor.

References

[1] Nantao Huang, "COMPARATIVE STUDY OF INDUCTION MOTOR STARTERS USING MATLAB SIMULINK," Milwaukee, Wisconsin, 2013.

[2] Burlington Butterworth–Heinemann, "*Power electronics handbook devices, circuits and applications*", 3rd ed., 2011.